Spatial resolution of a GEM readout TPC using the charge dispersion signal

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Abstract

A large volume Time Projection Chamber (TPC) is being considered for the central charged particle tracker for the detector for the proposed International Linear Collider (ILC). To meet the ILC-TPC spatial resolution challenge of $\sim 100~\mu$m with a manageable number of readout pads and channels of electronics, Micro Pattern Gas Detectors (MPGD) are being developed which could use pads comparable in width to the proportional-wire/cathode-pad TPC. We have built a prototype GEM readout TPC with 2 mm x 6 mm pads using the new concept of charge dispersion in MPGDs with a resistive anode. The dependence of transverse resolution on the drift distance has been measured for small angle tracks in cosmic ray tests without a magnetic field for $Ar:CO_2(90:10)$. The GEM-TPC resolution with charge dispersion readout is significantly better than previous measurements carried out with conventional direct charge readout techniques.

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1 Introduction

Large volume time projection chambers (TPC) [1, 2] have been used as high precision tracking detectors in many high energy physics experiments since the 1970s. A large volume TPC is also a prime track detector candidate for

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future experiments at the International Linear collider (ILC). However for the ILC application, it will be important to improve the spatial resolution capability for the TPC. A promising possibility is the replacement of the traditional proportional-wire/cathode-pad readout by a Micro Pattern Gas Detector (MPGD) like the Gas Electron Multiplier (GEM) [3, 4]. This would eliminate one of the major systematic errors which results from the so called $\mathbf{E} \times \mathbf{B}$ effect [5] that degrades the TPC spatial resolution.

The readout of a TPC with MPGD has several advantages but also some drawbacks, both of which are related to the confinement of the signal charge to a small spatial region due to reduced transverse in a high magnetic field. The advantage is that the localization has the potential to improve the double track resolution. The disadvantage with conventional MPGD direct charge readout technique is that it leads to difficulties with the determination of the signal position. For a nominal pad size of ~2 mm, signals may often be confined to one or two pads only making a centroid calculation less precise, in contrast to the proportional-wire/cathode-pad readout. A smaller pad width would lead to a better resolution but also to a large number of readout channels which may be difficult to manage for a large detector.

One possibility to improve the signal centroid determination and thus achieve good resolution with relatively wide pads is to use a MPGD with a resistive anode which disperses the avalanche charge and allows the signal to be reconstructed on several pads. The principle of charge dispersion has been proven previously [6] for a GEM using point X-ray source. The charge dispersion phenomenon and its application to MPGD-TPC readout are now well understood as shown in the excellent agreement of model simulations with experimental data [7]. In this paper, we present our first results of MPGD-TPC track resolution measurements with charge dispersion for cosmic-ray particles. The spatial resolution of a GEM-TPC is measured as a function of drift distance using the charge dispersion technique. $Ar:CO_2(90:10)$ was used as a fill gas to mimic the reduced transverse diffusion for a TPC in a high magnetic field. The results are compared to our previous measurements of GEM-TPC resolution [8] with direct charge readout for the same gas.

2   Experimental setup

A small 15 cm drift length double-GEM TPC used earlier for cosmic ray resolution studies with conventional direct charge readout [8] was modified for the measurements reported here. The standard anode pad readout plane was replaced with a resistive anode readout structure [6]. The new anode structure is fabricated by laminating a 25 μm thick film of carbon loaded Kapton with an effective surface resistivity of 530 KΩ/$\square$ to the readout pad PCB using a

double sided insulating adhesive. The adhesive provides a 50 μm gap between the resistive anode and the PCB. Taking the dielectric constant of the glue into account, the gap results in a capacitance density of C $\simeq$ 0.22 pF/mm^2. The film surface resistivity and the capacitance results in a RC coupling of the anode to the readout plane. An avalanche charge arriving at the anode surface disperses with the system RC time constant. Signals are induced on readout pads as explained in reference [6].

The TPC drift field for Ar:CO$_2$(90:10) at 300 V/cm was larger than in our previous measurements with direct charge readout for the same gas. From Magboltz [9], we find that the larger drift field increased the electron drift velocity from 8.9 to 22.75 $\mu m/ns$, and decreased the transverse diffusion slightly from 0.229 to 0.223 μm/$\sqrt{cm}$. Within measurement errors, the effective gas gain for the two measurements was about the same, about 6700.

The layout of the readout pad system contained 5 inner rows of 12 pads each (pad size: 2 mm $\times$ 6 mm), together with two large area outer pads whose signals are used for selecting cosmic events for analysis. Charge signals on the central 60 pads used for tracking were read out using Aleph proportional wire TPC readout preamplifiers. We used 200 MHz 8 bit FADCs, designed previously for another application, to digitize preamplifier signals directly without an intermediate shaper amplifier. Since charge dispersion pulses are slow and signals were integrated over a few hundred ns during analysis, 25 to 40 MHz FADCs would have been adequate.

The data analysis method is similar to that used in our previous publication [8] on GEM-TPC with conventional direct charge readout except for the amplitude reconstruction technique. For the direct charge measurement, signals result only from the charge deposit on a pad. Depending on the transverse diffusion in the TPC gas, one or more pads in a row have a signal. In this type of normal TPC readout, all signals have the same shape, $e.g.$ rise-time, and the maximum amplitude is proportional to the charge collected by the pad. The pad response function (PRF) can be evaluated from the known diffusion properties of the gas and readout geometry.

For the charge dispersion readout, in contrast, pads away from the region of direct charge collection on the anode may still see measurable signals due to the RC dispersion of the cluster charge on the resistive surface. The observed amplitude and the charge pulse shape depends on the distance of the pad with respect to the track ionization clusters and the characteristics of the front-end electronics. Pads seeing a part of the direct charge on the anode will have a prompt signal with a fast rise-time, while other pads with signals resulting only from charge dispersion will have a smaller slower rise-time delayed signal depending on the distance to the track. In principle, a determination of the track PRF is possible starting from the charge dispersion model. However,
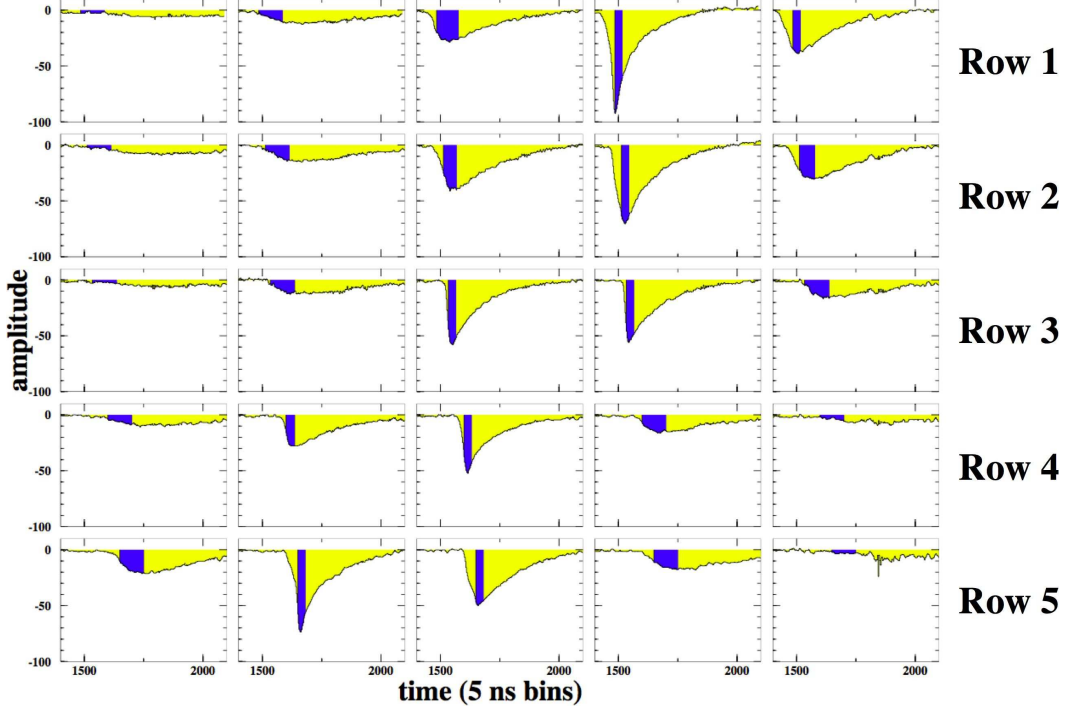
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Fig. 1. Track display plot showing observed pulse shapes for a cosmic ray track for the five rows of 2 mm x 6 mm GEM readout pads used for tracking. The dark shaded areas indicate the regions used to compute signal amplitudes to determine the pad response function (PRF), as explained in the text. The track parameters are: drift distance z = 1.97 cm, $\phi = 0.15$ radians and $\theta = -0.70$ radians.

small RC inhomogeneities of the resistive anode readout structure introduce systematic effects which make the theoretical PRF deviate from the measurement, as observed in Reference [7]. For the present analysis, the PRF as well as the systematic effects are determined empirically from the internal consistency of a subset of cosmic ray track data used only for calibration. The remaining part of the data is used for resolution studies.

As both the rise time and the pulse height carry track position information, the PRF will depend on the method used to reconstruct the pad signal amplitude from the measured pulse. The following method uses both the time and pulse height information to obtain a narrower PRF with shorter tails. For a given pad row, the largest pulse is identified and its amplitude calculated by maximizing the average pulse height in a 150 ns window. The large fast rise time pulse arises mainly from the primary charge. For a single track, adjacent pads in the row have delayed slower rising smaller signals; which reach their maximum peak pulse heights later. For these pads, the start of the integration time window is kept at the value obtained from the largest pad signal and the width is increased to maximize the reconstructed amplitude. The maximum window width is limited to 500 ns.

Fast pulses, from the primary charge, are thus averaged only over a short time

period, leading to a larger calculated amplitude. Slower rising smaller pulses are averaged over a longer time window, improving the signal to noise ratio. Since the start of the time window is determined by the main pulse in the row, late pulses will be reconstructed with a smaller computed amplitude as well leading to a suppression of the tails of the pad response function. Figure 1 shows the observed pulses for a cosmic ray track for the five tracking rows of pads. The time bins used for the determination of the amplitudes are also indicated. Differences in the shapes between the main pulse dominated by primary charge and pulses from charge dispersion on pads farther away are visible.

The resolution study was restricted to track angles $|\phi| < 5°$. The track fit of the reconstruction analysis made use of a pad response function PRF determined from the calibration data set. The PRF was determined as a function of drift distance and as mentioned before, the calibration data set was not used for resolution studies.

Figure 2a shows the PRF data for drift distances up to 1 cm. The relative amplitude is shown as a function of the distance between the pad-center and the track. The PRF was determined in 1 cm steps and parameterized with a ratio of two symmetric 4th order polynomials:

$$PRF(x, \Gamma, \Delta, a, b) = \frac{1 + a_2 x^2 + a_4 x^4}{1 + b_2 x^2 + b_4 x^4} \tag{1}$$

with

$$a_2 = -(2/\Delta)^2 (1 + a)$$
$$a_4 = (2/\Delta)^4 a$$
$$b_2 = (2/\Gamma)^2 \left(1 - b - 2(1 + a) \left(\frac{\Gamma}{\Delta} \right)^2 + 2a \left(\frac{\Gamma}{\Delta} \right)^4 \right)$$
$$b_4 = (2/\Gamma)^4 b,$$

where in principle all parameters, full-width-half-maximum $FWHM$ (Γ), base width Δ, and scale parameters a and b, depend on the drift distance. For the present data set, a linear parameterization could be used for the square of $FWHM$ as shown in Figure 2b. The other parameters at $b = 0$, $a = -0.3$ and $\Delta = 11.9$ mm were held constant.

Since the track fit uses a χ^2 minimization, the amplitude measurement errors must also be determined from the data. In our case, this error is dominated by systematic effects leading to a mainly linear dependence on the amplitude.

3   Analysis and results

As in our previous paper [8], the track parameters x_0 and ϕ are determined from a global fit to all pad amplitudes of a given event. We use a right-handed coordinate system with the x-coordinate horizontal and the y-coordinate par-
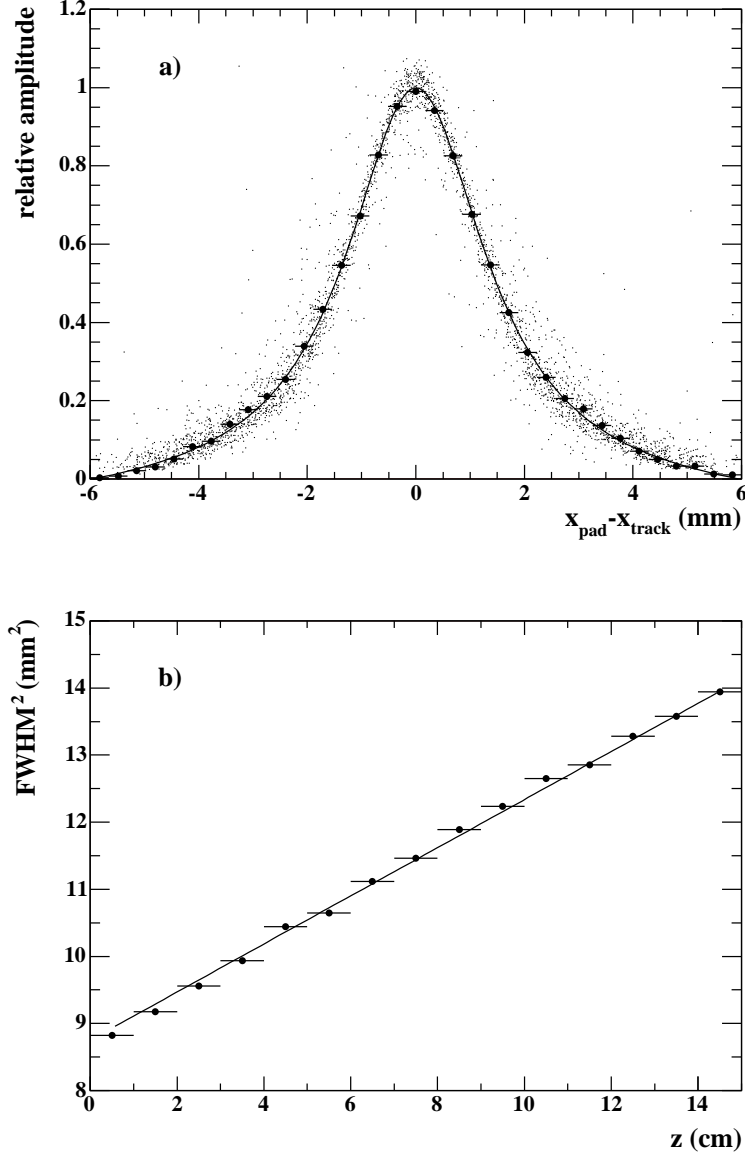

Fig. 2. a) Determination of the pad response function (PRF) from the calibration data set for the first 1 cm drift. The figure shows measured relative pulse amplitudes as a function of the track x coordinate relative to pad centres and the fit to the PRF parametric form given by Eq. 1. b) The PRF as a function of drift distance was determined in 1 cm steps. The dependence of the square of the $FWHM$ of the PRF on the drift distance was found to be linear.

Fig. 3. Bias in the determination of track position before and after correction. The figure shows position residuals ($x_{\text{row}} - x_{\text{track}}$) for row 4 (see Fig 1) as a function of x_{track}, a) before and b) after bias correction.

allel to the pad length; the z-coordinate corresponds to the drift distance with $z = 0$ at the first GEM stage. The azimuthal angle ϕ and the polar angle θ are measured with respect to the y-axis. The position in a row x_{row} is determined from a separate one-parameter track fit to this row only using the known track angle ϕ. Figure 3a shows the mean of the track residuals $x_{\text{row}} - x_{\text{track}}$ for row 4 (see Fig 1) as a function of $x_{\text{track}} = x_0 + \tan\phi * y_{\text{row}}$, where y_{row} is the y position of the row. A bias of up to 130 μm is observed which we attribute to small local variations in the RC from imperfections in the quality of materials and technique used presently in laminating the resistive anode readout assembly. The bias is intrinsic to the detector and does not change with time. It can therefore be easily corrected. The calibration data set used for the PRF determination is also used to determine the bias correction for each pad row in 500 μm steps. Figure 3b shows the mean track residuals for the central pad row after bias correction. The remaining bias after correction was small.

Figure 4 shows the distribution of the residuals for tracks with $|\phi| < 5°$ and small drift distance $z < 1$ cm. As in our previous publication [8] the resolution is given by the geometric mean of standard deviations of residuals from track fits done in two different ways: including and excluding the row for which the resolution is being determined. The measured resolution as a function of drift

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distance is shown in Figure 5 together with a fit to the function:

$$s = \sqrt{s_0^2 + \frac{C_{\mathrm{D}}^2 z}{N_{\mathrm{eff}}}} \quad , \tag{2}$$

where s_0 is the resolution at $z = 0$, C_D is the transverse diffusion constant and N_{eff} is the effective number of electrons along the track in a row.

Electronic noise and systematic effects contribute to the constant term s_0, the resolution at zero drift distance. The constant term s_0 is about 80 μm for the charge dispersion readout. In contrast, as shown in Figure 5, the TPC resolution with the conventional GEM readout for drift distances approaching zero would be much larger (138 μm at 5 mm), due to lack of precision in pad centroid determination from diffusion. The resolution for the conventional GEM readout improves with increasing transverse diffusion for larger drift distances. Nevertheless, the TPC resolution obtained with the charge dispersion readout remains better than with the conventional GEM readout [8] even for larger drift distances. This is due to the fact that the charge dispersion phenomena can be completely described by material properties and geometry and the centroid of the dispersed charge signals on the resistive anode can be accurately determined, in contrast to centroid determination from diffusion, which is statistical in nature.
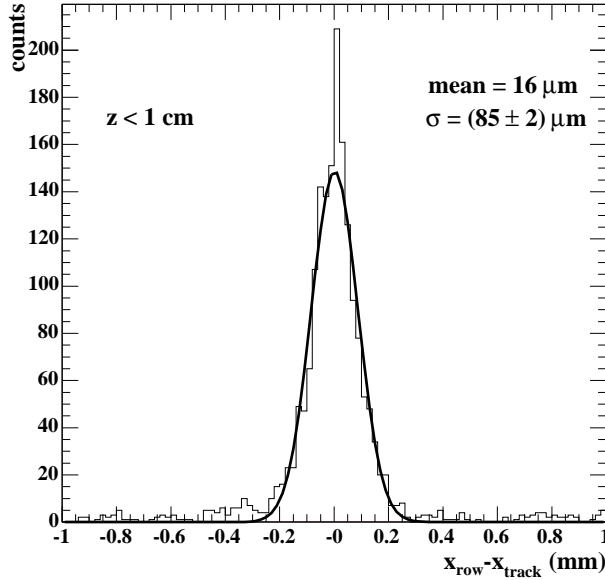

Fig. 4. Position residuals $x_{\mathrm{row}} - x_{\mathrm{track}}$ for short drift distance $z < 1$ cm and track angles $|\phi| < 5°$ after bias correction. The mean corresponds to the remaining bias.
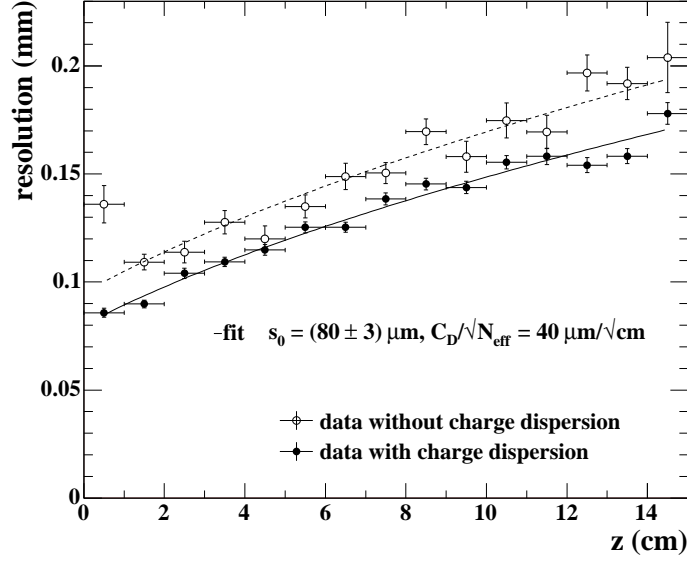
Fig. 5. Transverse resolution for track angles $|\phi| < 5°$ as a function of drift distance z for 2 mm wide pads. The data with charge dispersion is fitted to the resolution expected from diffusion in the TPC gas and electron statistics (Eq. 2) (solid line). For comparison, the GEM-TPC resolution with direct charge readout from our previous work [8] is also shown (dashed line).

4 Summary and outlook

A GEM-TPC with a charge dispersion readout system incorporating a resistive anode has been used to measure particle track resolutions for the first time. The resistive anode allows a controlled dispersion of the track charge clusters over several pads which can be used for a precise determination of the charge centroid. Using 2 mm x 6 mm pads, we have shown that charge dispersion improves the GEM-TPC resolution significantly over that achievable with conventional direct charge readout, both at short and at long drift distances. Imperfections in the resistive anode assembly and materials lead to a position measurement bias which can be easily corrected. The bias remaining after correction is small. With improvements in fabrication techniques and the quality of materials, the measurement bias will be reduced further. The TPC pad readout signals were digitized at 200 MHz for the results reported here. We are in the process of developing slower 25 to 40 MHz digitizers which will be adequate for these type of measurements.

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Acknowledgments

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